ScanSAR Interferometry for SRTM: First Results and Algorithm Comparisons for the Prototype Global Topographic Processing System

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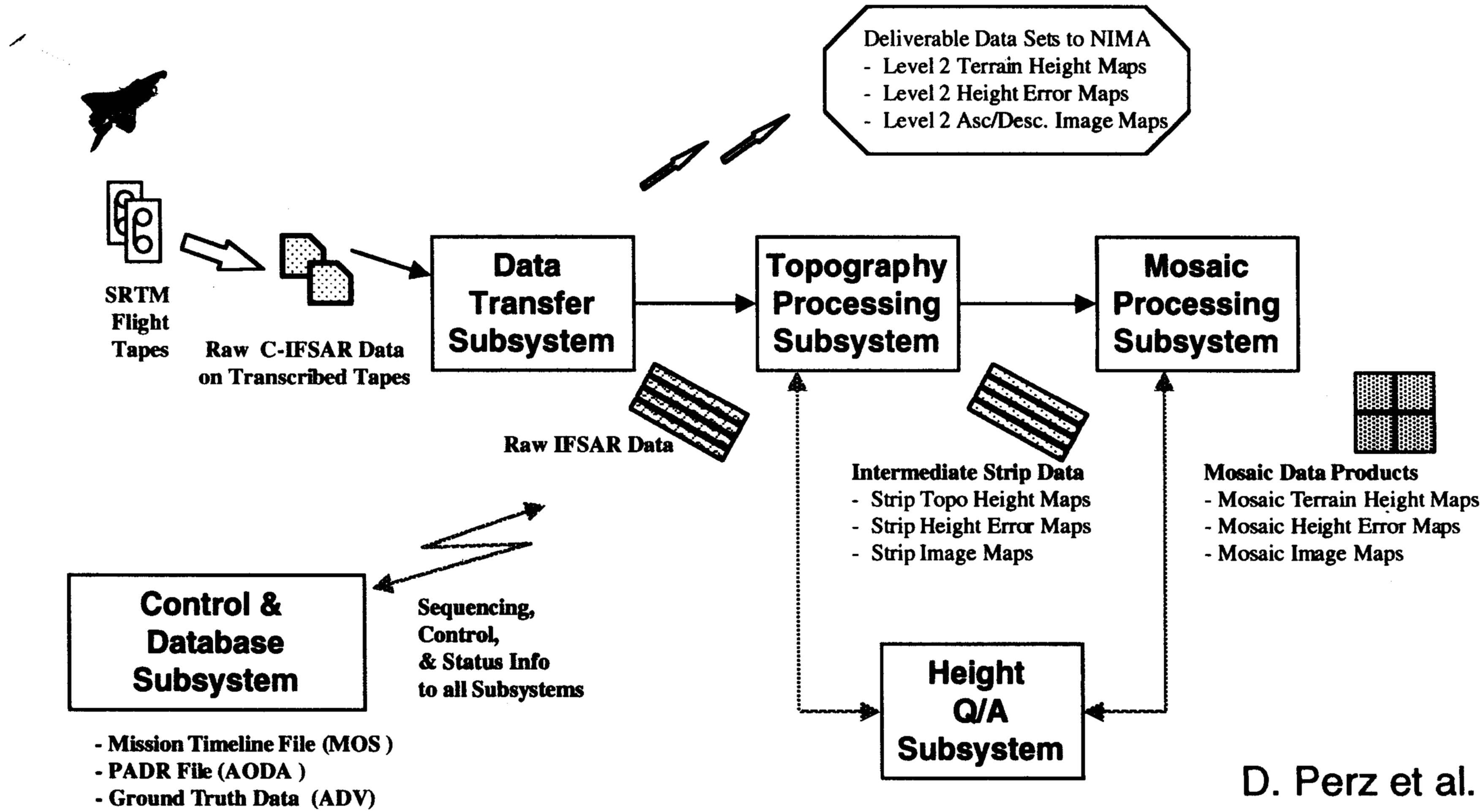
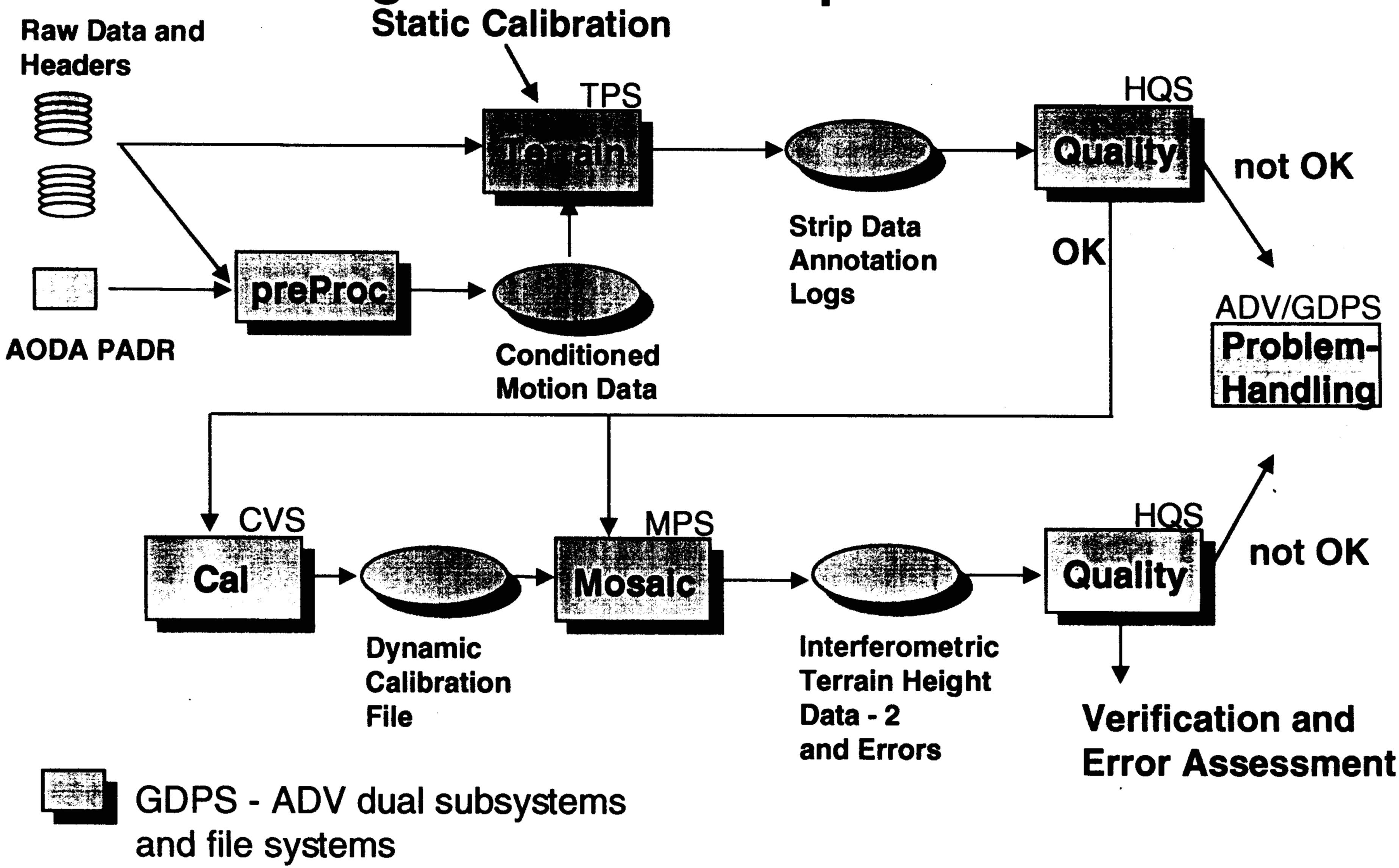
SRTM Ground Data Processing System



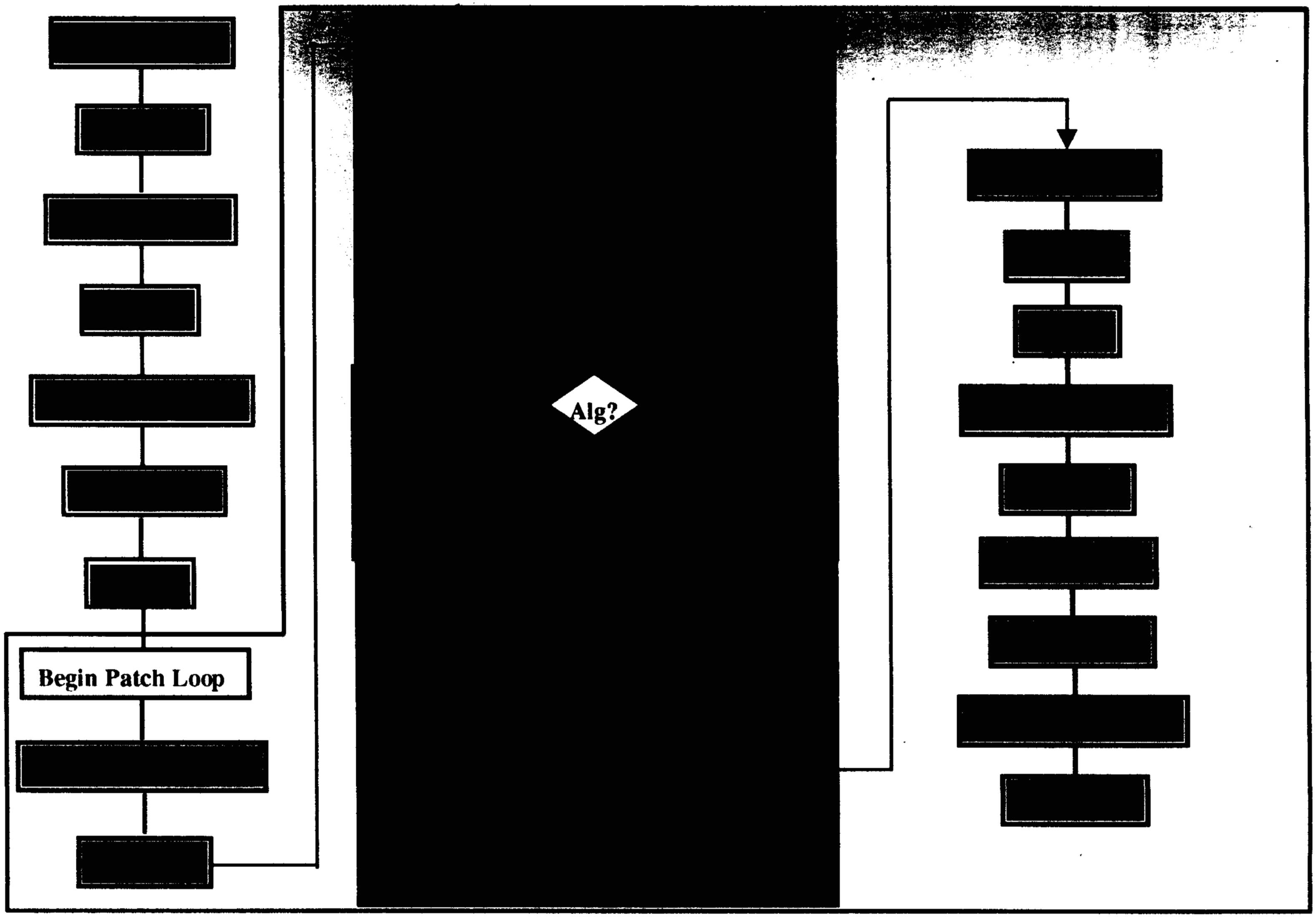
D. Perz et al.

Algorithmic Conceptual Flow



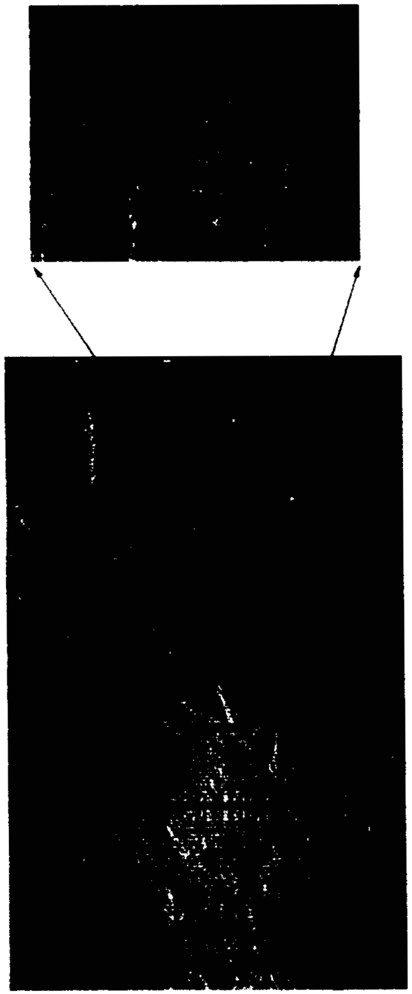
NASA JPL

Topographic Processing System

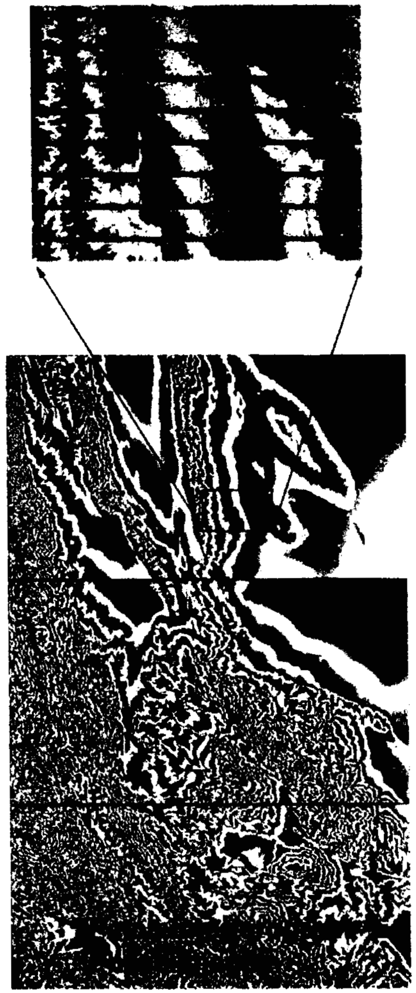


TPS Preliminary SRTM Processing

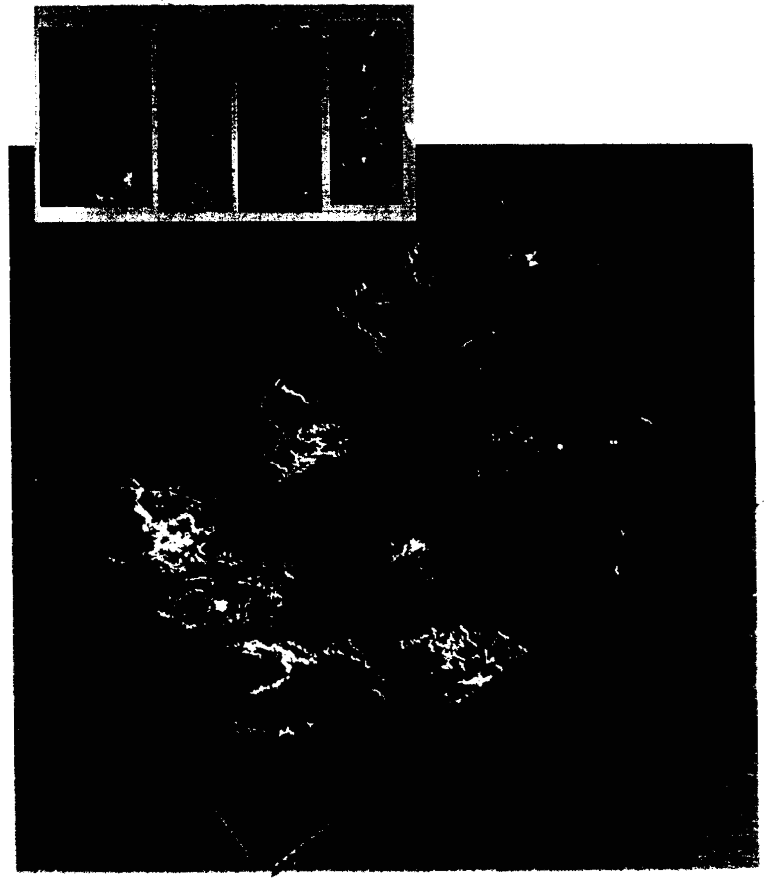
Burst Interferogram
Brightness Images



Burst Interferogram
Phase Images



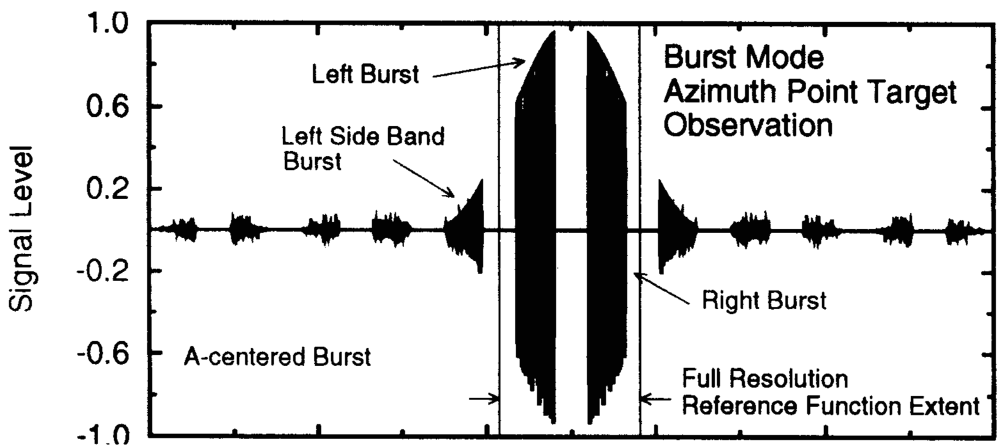
Uncalibrated Strips

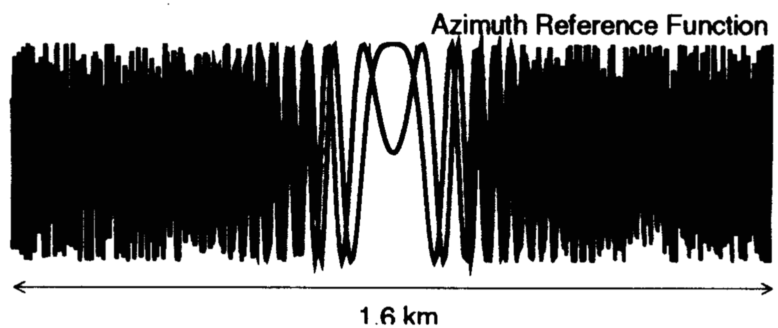


Burst Processing Algorithms

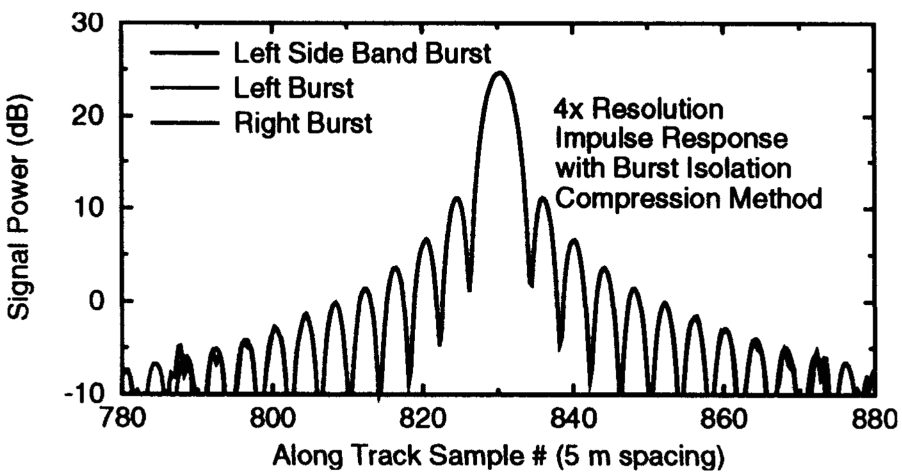
- Problem:
  - Choose algorithm to perform azimuth compression over the synthetic aperture, taking into account the burst discontinuities in the observing strategy
    - performance accuracy
    - efficiency
    - simplicity and ease of implementation
- Options:
  - Strip-Mode Processing - Standard Doppler processing as though there were no burst strategy employed
  - SPECAN Processing (M. Jin) - Deramp FFT method employed in RADARSAT ScanSAR processor
  - Burst Isolated Doppler Processing
  - Modified SPECAN Processing

Burst-Isolated Compression in Burst Mode SAR



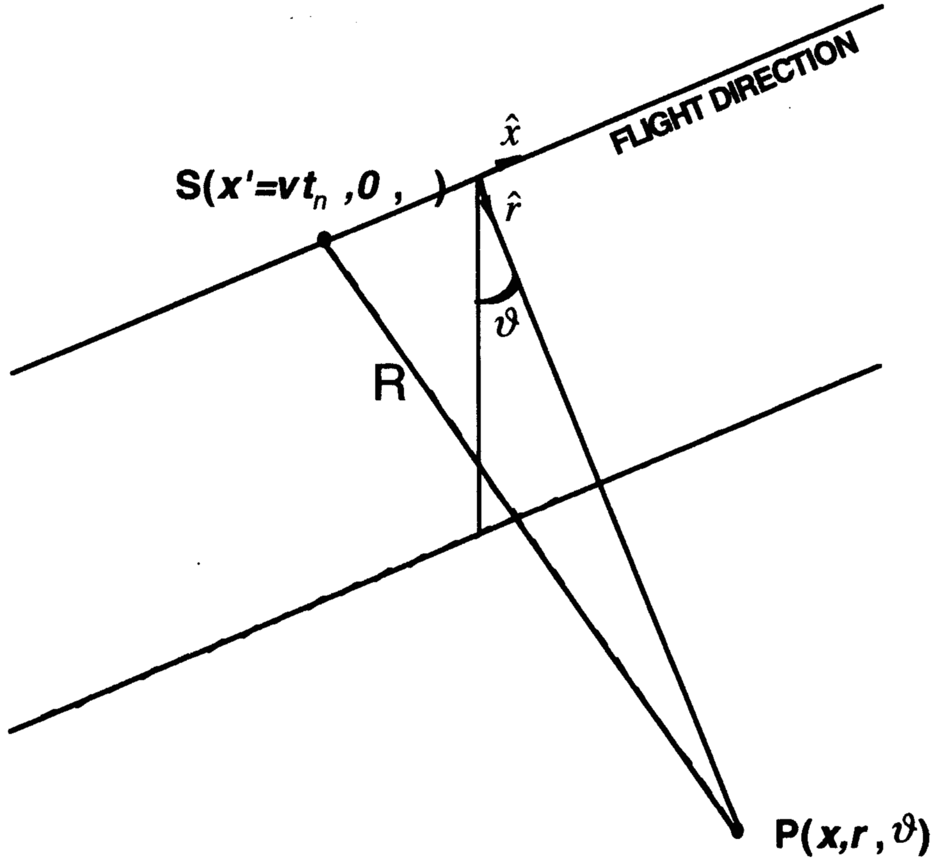


- Convolve Each Burst of Observation Individually With Reference Function



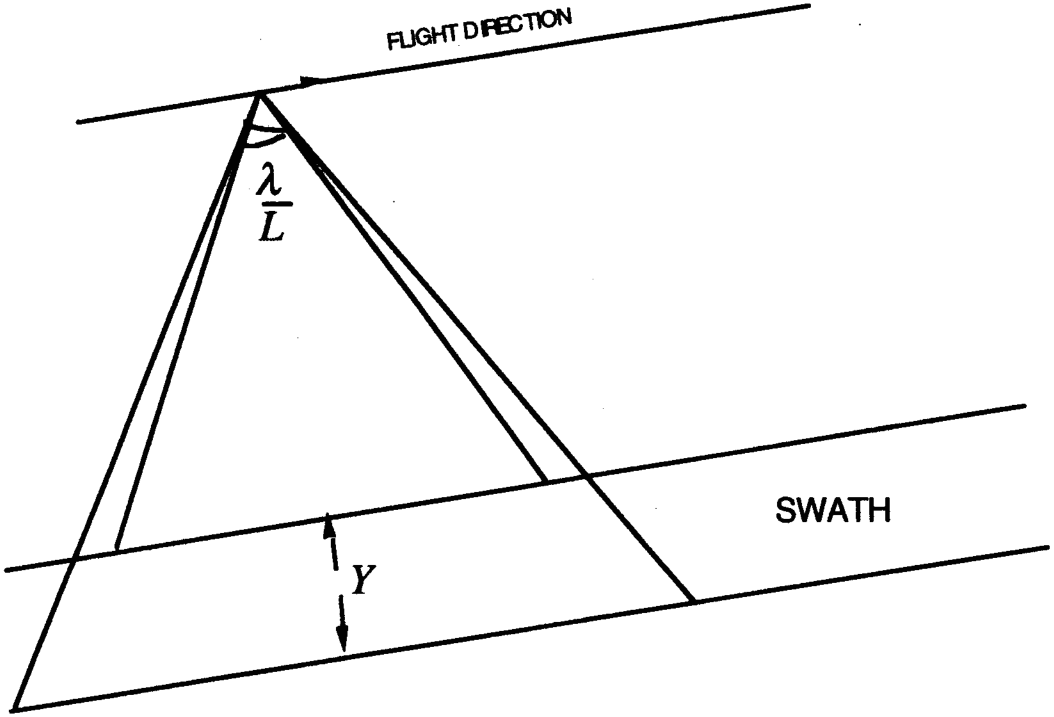
Each Point Target Response After Azimuth Compression Is SINC-like, Main Lobe Width 2L

SAR Geometry



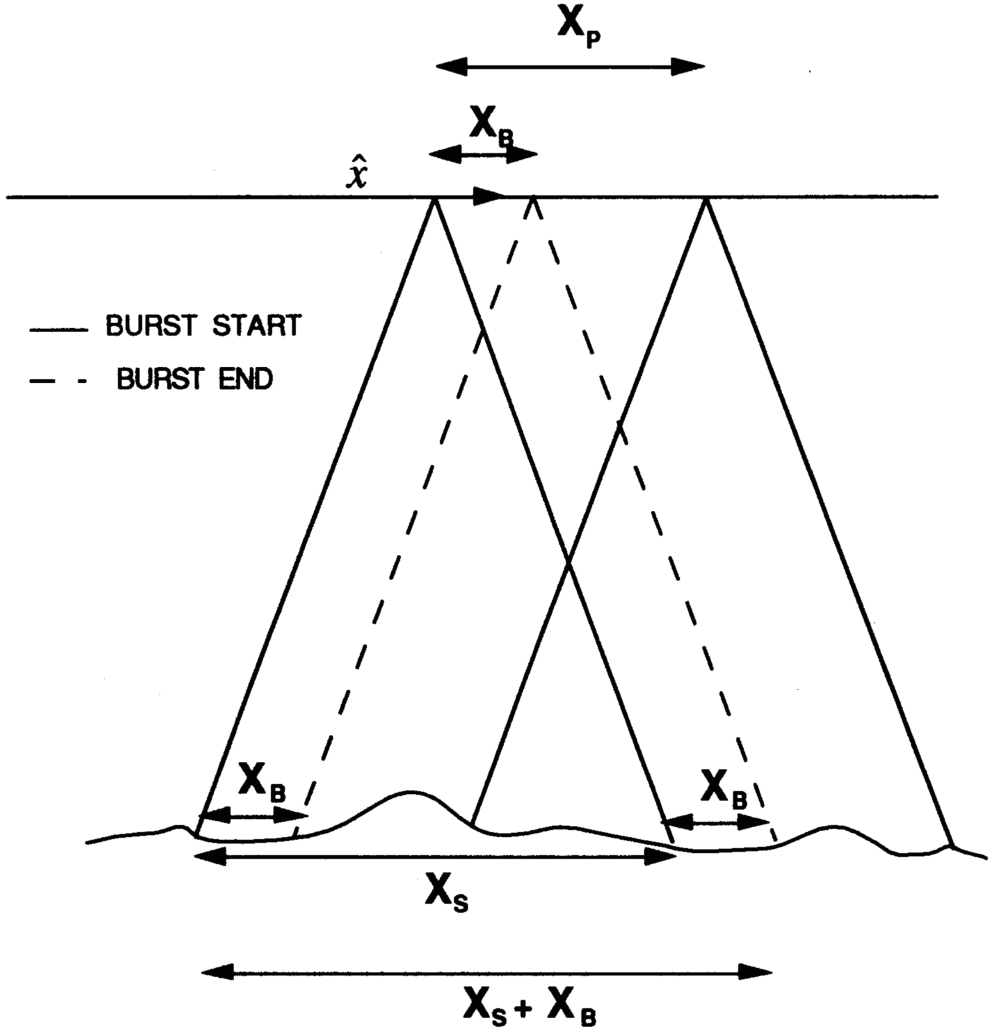
$$R=\sqrt{(x'-x)^2+r^2}\approx r+\frac{(x'-x)^2}{2r}$$

Beam Geometry



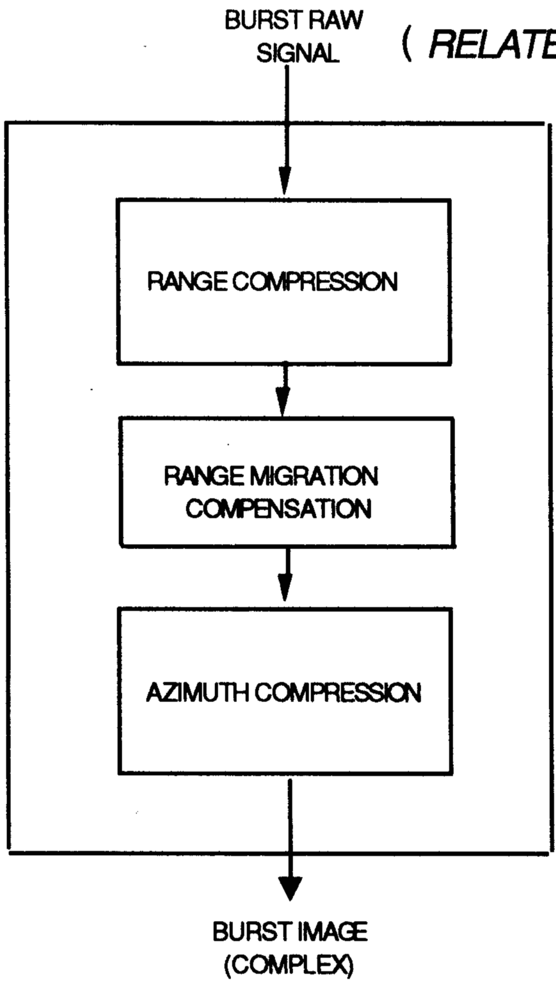
$$\frac{2v}{L} = B_d \leq PRF \leq f(Y)$$

Burst Geometry



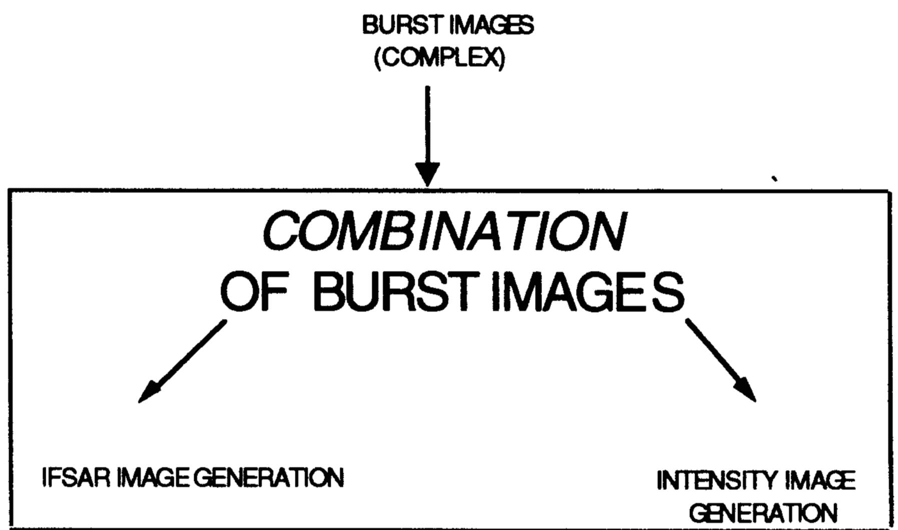
Processing Schematic

(*RELATED* TO X_B)

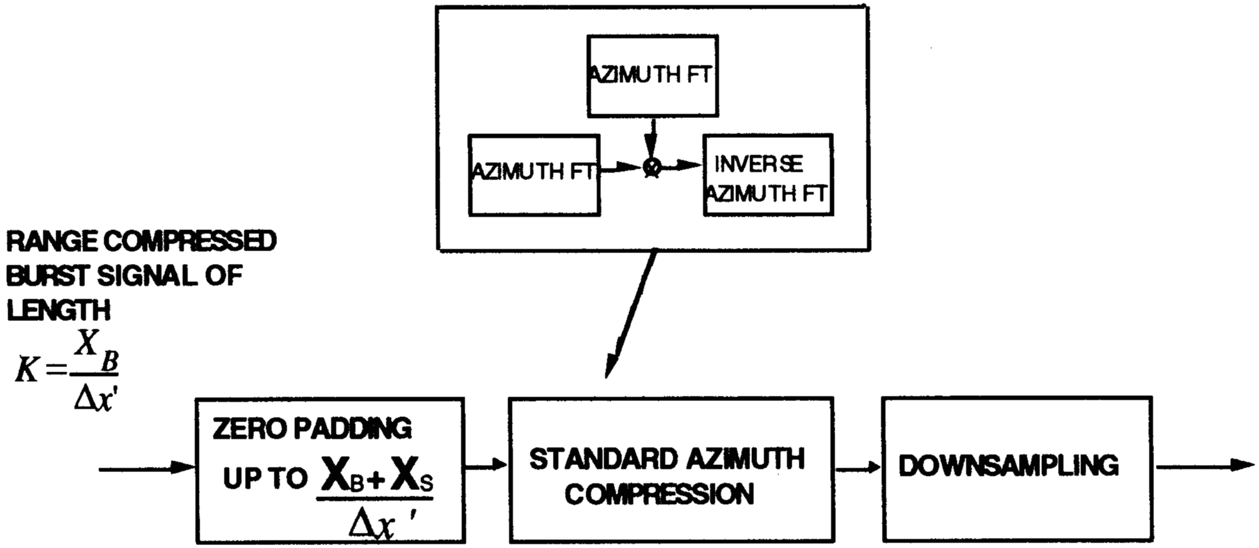


SINGLE BURST IMAGE GENERATION

(*RELATED* TO X_B+X_S)



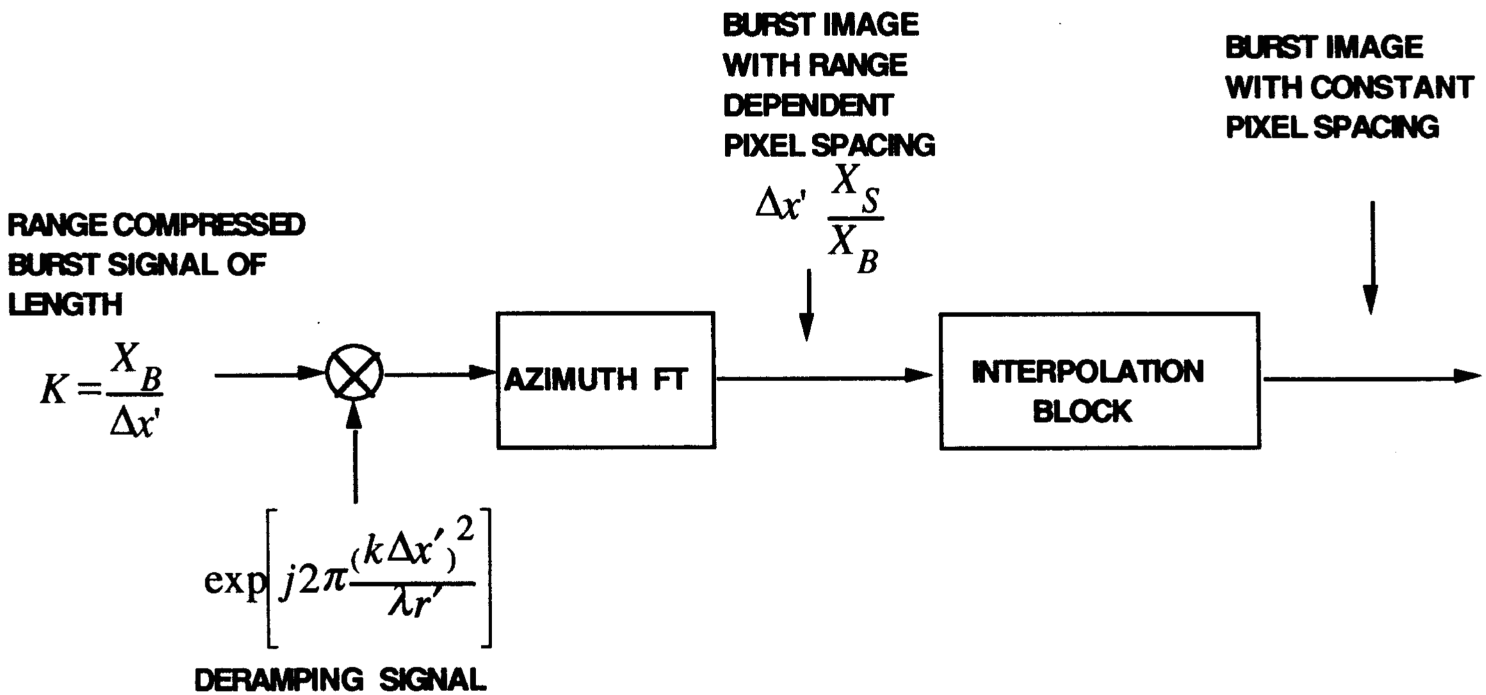
Azimuth Compression: Standard Doppler



NOTE THAT THE PIXEL DIMENSION $\Delta x' = \frac{v}{PRF}$ IS SMALLER THEN

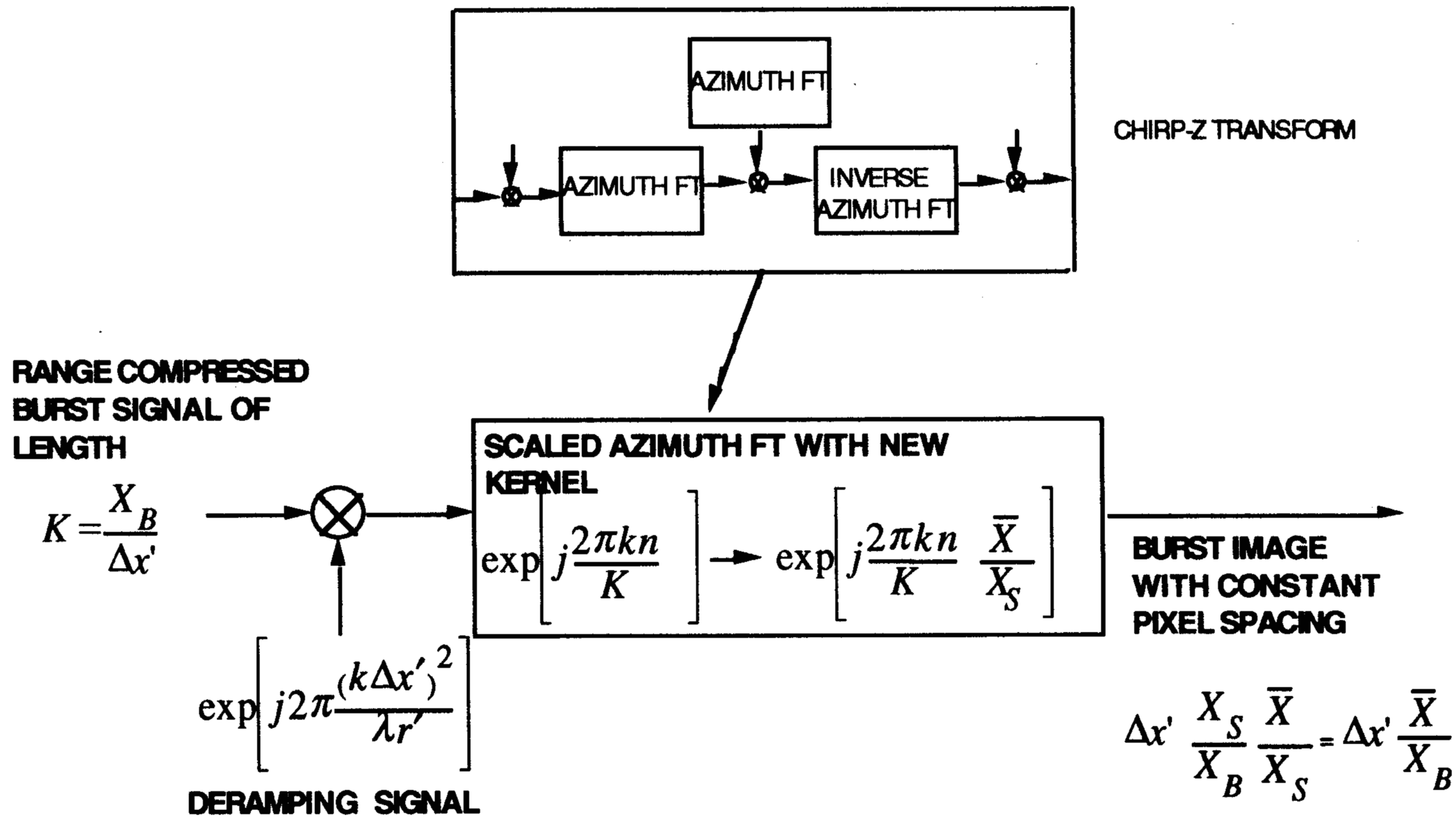
THE RESOLUTION $\Delta x = \frac{L}{2} \frac{X_S}{X_B}$

Azimuth Compression: Standard SPECAN



WITH $k = 0, K-1$ **AND** $X_S = \frac{\lambda}{L} r'$

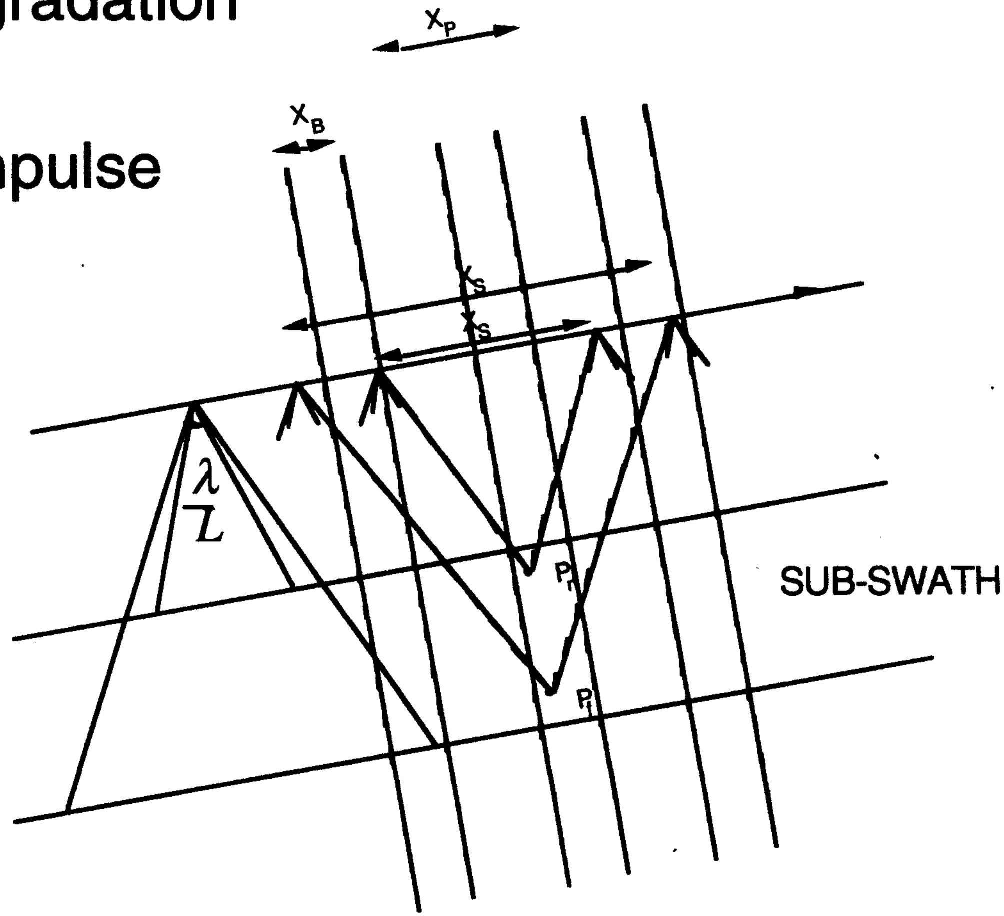
Azimuth Compression: Modified SPECAN



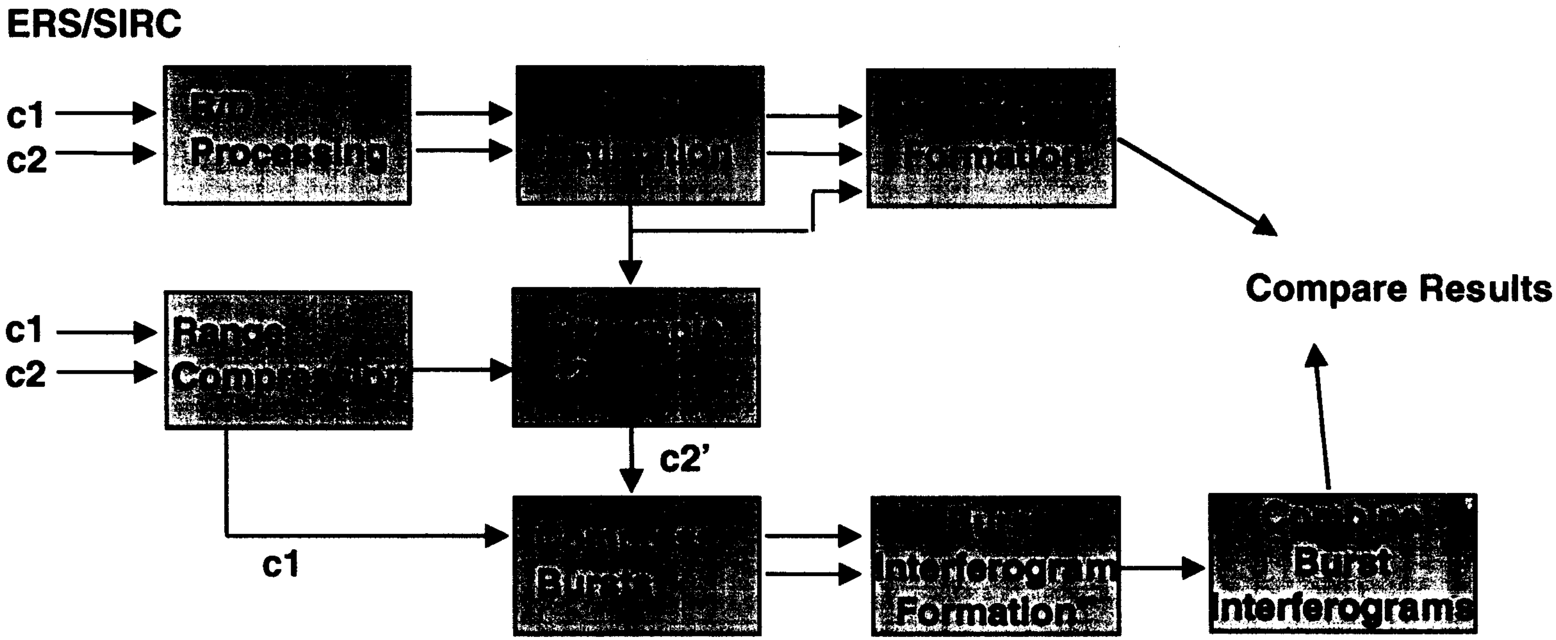
WITH $k = 0, K-1$ **AND** $X_S = \frac{\lambda}{L} r'$, $\bar{X} = \frac{\lambda}{L} \vec{r}$

Burst Processing Issues

- Multiple Looks in Azimuth
- Azimuth resolution degradation by X_S / X_B
- Azimuth Dependent Impulse Response
- Amplitude Scalloping



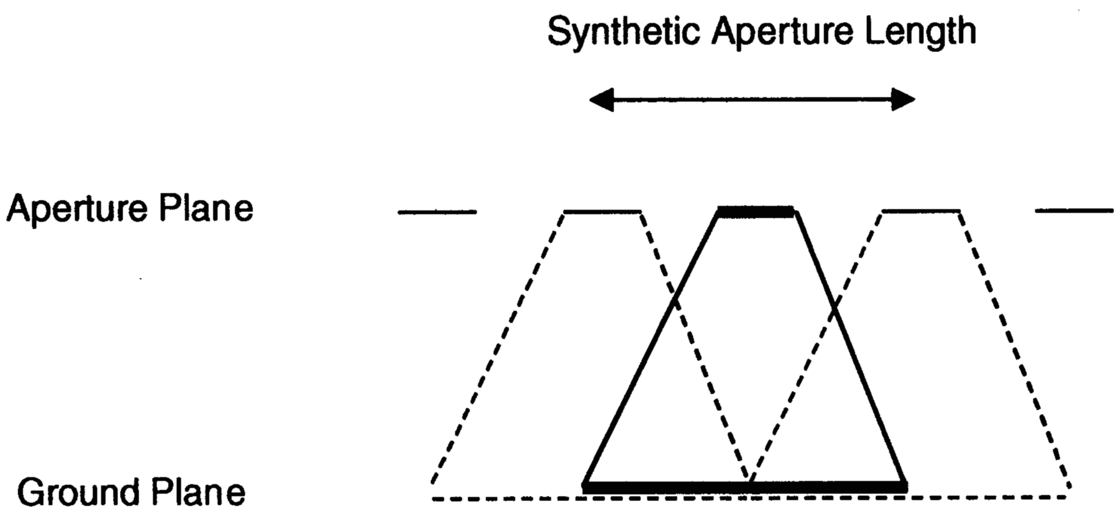
Burst Compress Test Scheme



* Burst Compression software allows Doppler or Modified SPECAN Processing, with variable burst length, interburst period, decimation ratio, stretch and shift (for M/S).

**Phase characteristics can also be compared by forming cross-method interferograms.

Illustration of Burst Interferogram Combination



Interferograms formed from each burst overlap in the ground plane.

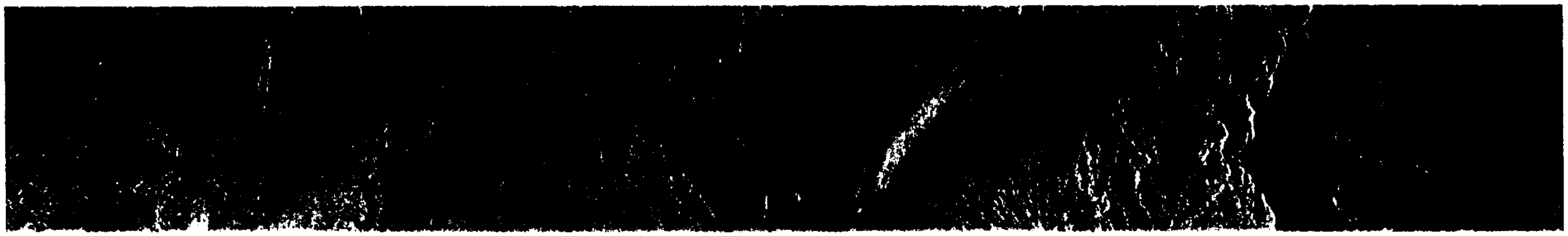
Interferograms are coherently added to recover looks in processing.

Doppler and Modified SPECAN processing ensure constant mapping from burst to burst.

ERS Interferogram Test Example

Standard Strip Mode Interferogram Amplitude (4 looks; then 4x4 more)

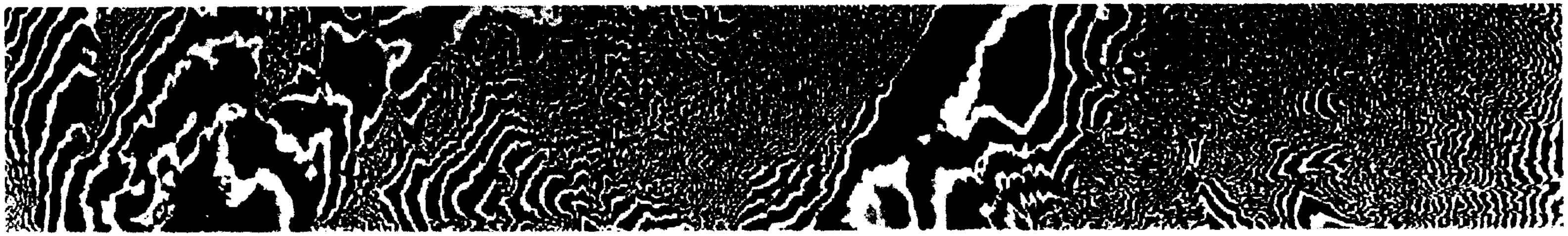
Burst Processed Interferogram Amplitude (1/4 aperture; 2 looks; then 4x4 more)



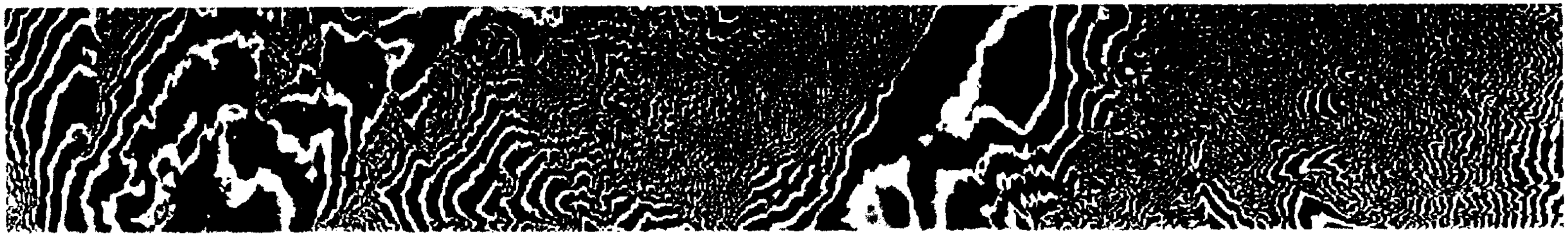
Note Amplitude Scalloping

ERS Interferogram Test Example

Standard Strip Mode Interferogram Phase (4 looks; then 4x4 more)



Burst Processed Interferogram Phase (1/4 aperture; 2 looks; then 4x4 more)



Interferogram Phase Difference

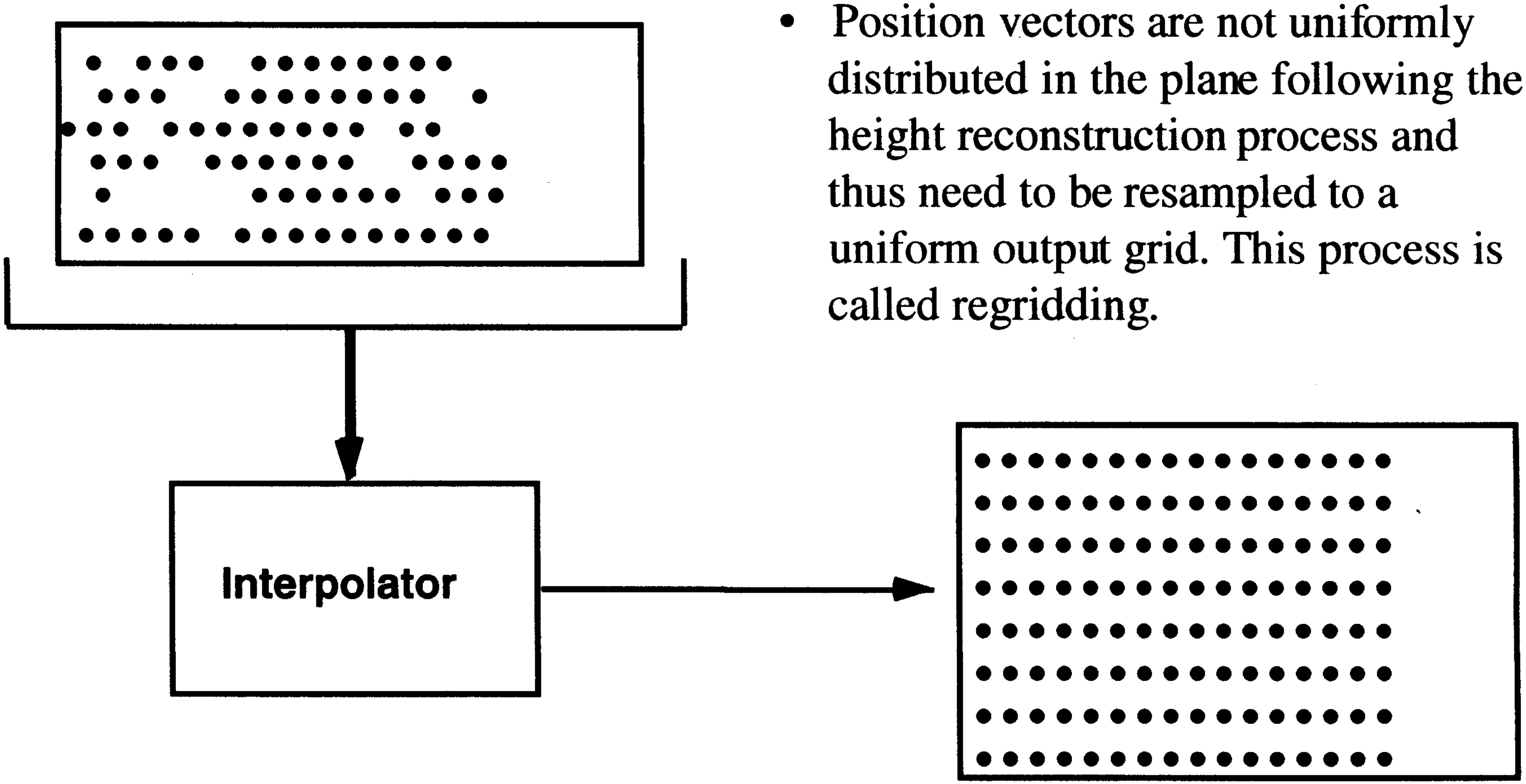
Motion Data Characteristics and Impact on Burst Mode Processing

- Plot of AODA data motions
- Plot of residual errors if uncompensated

SRTM Burst Algorithm Comparison

Regridding

- Position vectors are not uniformly distributed in the plane following the height reconstruction process and thus need to be resampled to a uniform output grid. This process is called regridding.

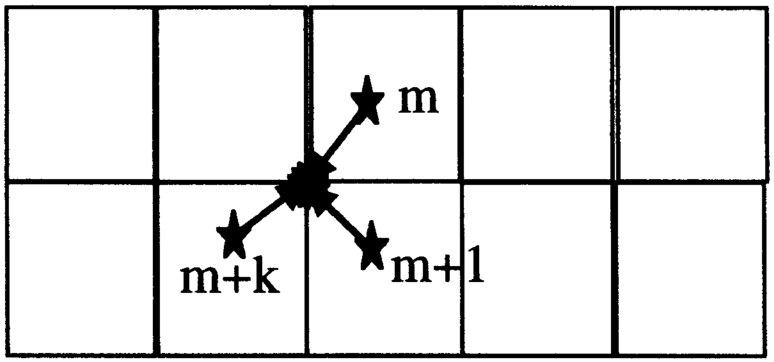


Regridding Options

- The problem of interpolating data that is not sampled on a uniform grid, that is noisy, and contains gaps is a difficult problem.
- Several interpolation algorithms have been implemented
  - Nearest neighbor - Fast and easy but shows some artifacts in shaded relief images.
  - Simplical interpolator - uses plane going through three points containing point where interpolation is required. Reasonably fast and accurate.
  - Convolutional - uses a windowed Gaussian approximating the optimal prolate spheroidal weighting function for a specified bandwidth.
  - First or second order surface fitting - Uses the height data centered in a box about a given point and does a weighted least squares surface fit.

Some Bookkeeping Details

- After height reconstruction each unwrapped phase point consists of a triple of numbers, the SCH coordinates of that point. Note that this point does not necessarily lie on an output grid point. To preserve the full information of the reconstructed target and have a convenient referencing frame relative to the output grid each reconstructed point is assigned a number which is stored in an array indexed by output grid location.



- Multiple points can be assigned to the same location (until the buffer is full - nominally set to five points)

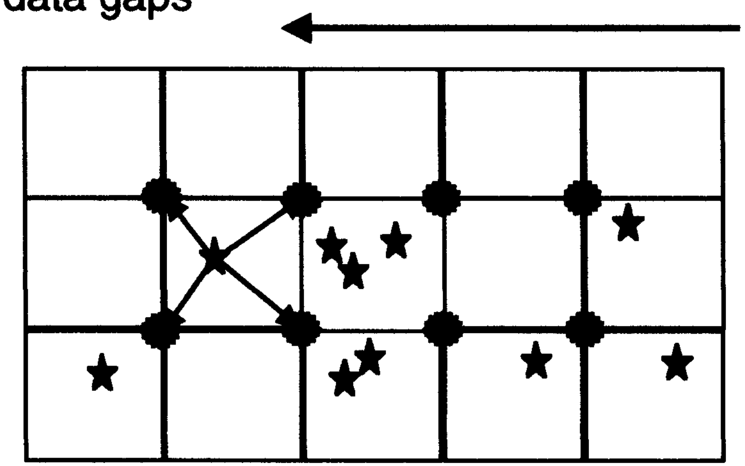
- Location in output grid (s_l,c_l) is determined by nearest neighbor location

$$c_l = \left[\frac{c - c_o}{\Delta c}\right] \qquad s_l = \left[\frac{s - s_o}{\Delta s}\right]$$

where (s,c) are the target s,c coordinates, c_o,s_o are the map offsets and Δs, Δc are the pixel dimensions.

Nearest Neighbor

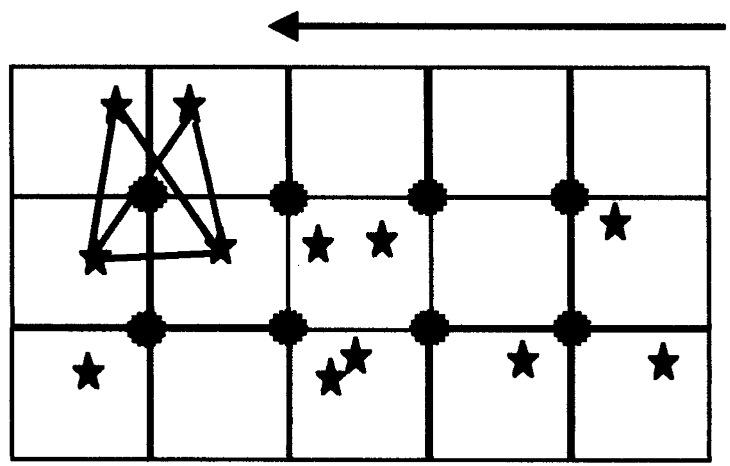
- This is the simplest algorithm considered for regridding the height and other data layers.
- Very efficient and easy to implement.
- Used very successfully in the TOPSAR and IFSARE processors.
- Drawbacks include
  - no further reduction of height noise
  - occasional regridding artifacts such as
    - terracing of amplitude and height data
    - height ramps due to range dependent noise levels
    - valleys can be rounded out or filled
    - “Pin prick” data gaps



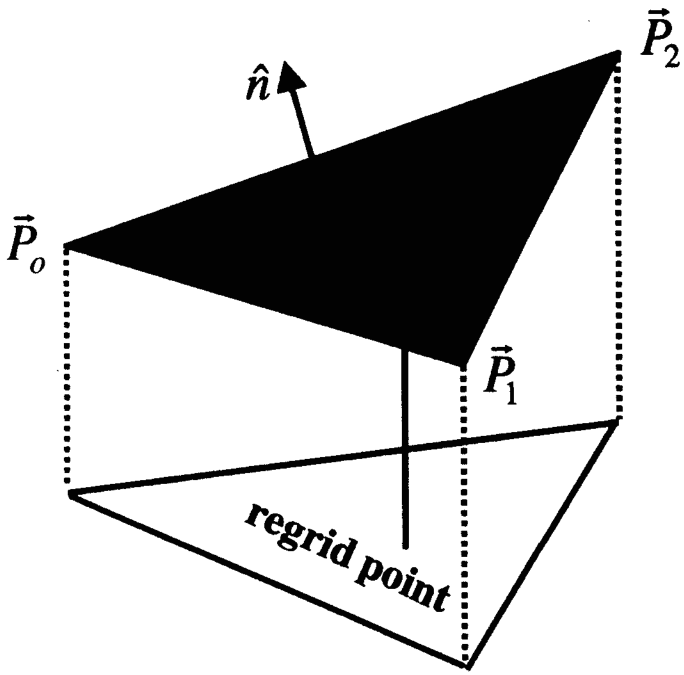
- Data written from near to far range

Simplical Regridding

- Regrids the data using a planar "fit" with three points enclosing the point where regridded value is desired.
- Several criteria are considered for selecting which triangle (or simplex) to use when obtaining height value at regrid point
  - simplex of minimal area containing regrid point
  - simplex with vertex closest to regrid point
  - simplex with minimal height error
  - simplex with large isoperimetric ratio
- More robust than nearest neighbor in avoiding pin pricks
- Some reduction in height noise with this method.
- Used and well tested in mosaicking software.



Simplical Regridding Formulas



- Plane passing through three points satisfies the equation

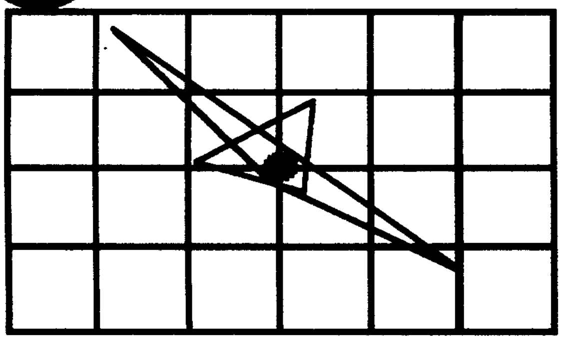
$$\left(\vec{P}-\vec{P}_o\right)\bullet\hat{n}=0$$

where $\vec{P}_o,\vec{P}_1,\vec{P}_2$ are three known points in the plane and $\hat{n}$ is the normal to the plane given by

$$\hat{n}=\left(\vec{P}_1-\vec{P}_o\right)\times\left(\vec{P}_2-\vec{P}_o\right)$$

- Three points are chosen such that
  - Regrid point lies in the interior of a triangle of three points for which the position vectors are known
  - Triangle has isoperimetric ratio larger than .3 (prevents using long skinny triangles)
  - Points are within a specified distance to regrid point
  - Smallest height variance

Details on Simplex Selection



—— Selected Simplex

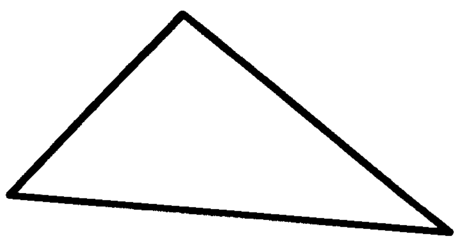
—— Rejected Simplex

- Take point of minimal height variance at each lattice point in output grid.
- Loop over all set of three vertices and eliminate simplicies
  - do not contain regrid point
  - are two thin and narrow (use isoperimetric ratio)
  - distance of closest vertex in simplex to regrid point is two large
- If multiple candidates exist take one with minimal height variance

$$\text{Isoperimetric ratio} = \frac{4\pi A}{P^2}$$

Note: This value is always less than or equal to one. Attains the value of one for a circle.

Smaller isoperimetric ratio



Larger isoperimetric ratio

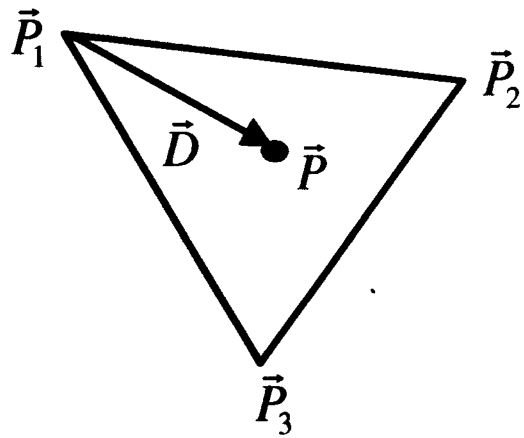
Height Variance Computation

JPL

- From the equation of the plane used for simplical interpolation the regridded height, h_f in term of the heights at the three vertices has the form

$$h_f = \left(1 + \frac{(\vec{D}_{32} \times \vec{D})_z}{(\vec{D}_{21} \times \vec{D}_{31})_z}\right) h_1 + \left(\frac{(\vec{D}_{31} \times \vec{D})_z}{(\vec{D}_{21} \times \vec{D}_{31})_z}\right) h_2 + \left(\frac{(\vec{D}_{21} \times \vec{D})_z}{(\vec{D}_{21} \times \vec{D}_{31})_z}\right) h_3$$

where $\vec{D}_{ij} = \vec{P}_i - \vec{P}_j$ and $\vec{D} = \vec{P} - \vec{P}_1$



- The height variance of the regrid point is given by

$$\sigma_{h_f} = \sqrt{\sum_{i=1}^{3} k_i^2 \sigma_{h_i}^2}$$

where the k_i are the coefficients of the h_i given above.

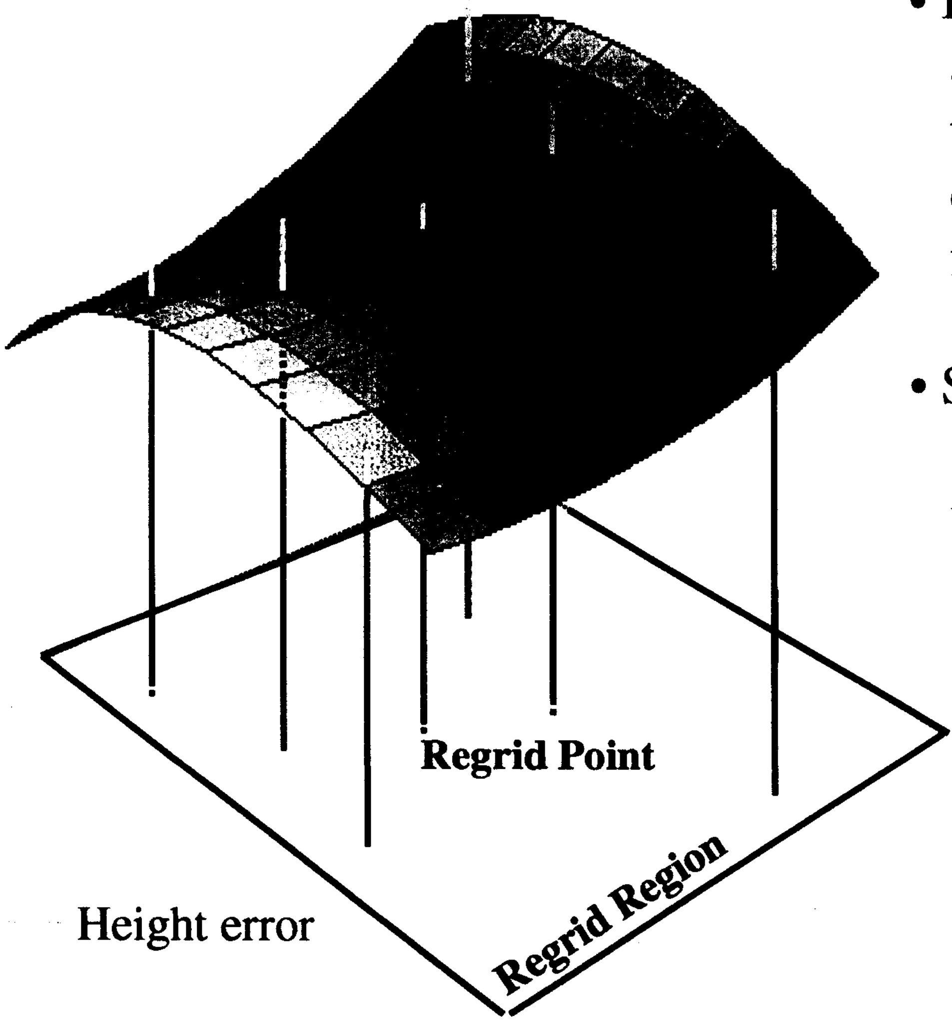
- Note if the regrid point is at the median of the triangle then the k_i are all equal to 1/3. Assuming height variances are all equal there is a reduction in the height variance by $\sqrt{3}$.

Surface Fitting and Adaptive Regridding

- The surface fitting regrid method fits a quadratic surface to points within a specified region containing the regrid point. This method has several advantages
  - reduction in height noise that depends roughly on the inverse of the square root of the number of points in the region used to make the fit
  - helps eliminate pin prick holes in the DEM
  - can simultaneously estimate slope and curvature information
- The region used for fitting plus the weights can be adjusted to adaptively smooth the noise at the expense of spatial resolution
  - standard weighting is by the by the expected height variance, σ, determined from the interferometric correlation
  - to reduce the effect of points far from the regrid point the weighting can be increased using a simple distance dependent additional weighting

$$w(\vec{x}-\vec{x}_o)=\frac{k}{\sigma}\left|\vec{x}-\vec{x}_o\right|^{n}$$

Surface Fitting Regrid Geometry



- Box size and additional weighting adjusted depending upon the ratio of the RMS surface elevation to the mean expected height error as determined from the interferometric correlation.

- Surface fitting acts as a low pass filter so certain higher frequency components will be lost in the resampling process.

Convolutional Regridding Formulas

- The convolutional regridder determines the height at point as sum of all heights points within a box, B, centered at the desired regrid point weighted by the convolutional kernel weights which a function of the distance from the regrid point.

$$h(\vec{p}_0) = \sum_{\vec{p} \in B} w(\vec{p} - \vec{p}_o) h(\vec{p})$$

- The height error estimate is obtained from the local height errors estimates for each point in the box weighted by the derivatives of the kernel with respect to the spatial variables.

$$\sigma_h(\vec{p}_0) = \sqrt{\sum_{\vec{p} \in B} \left(\frac{\partial w}{\partial \vec{p}} (\vec{p} - \vec{p}_o) \right)^2 \sigma_h^2(\vec{p})}$$

- As with the surface fitting algorithm an estimate of the slope and curvature can be obtained using the first and second derivatives of the convolutional kernel.

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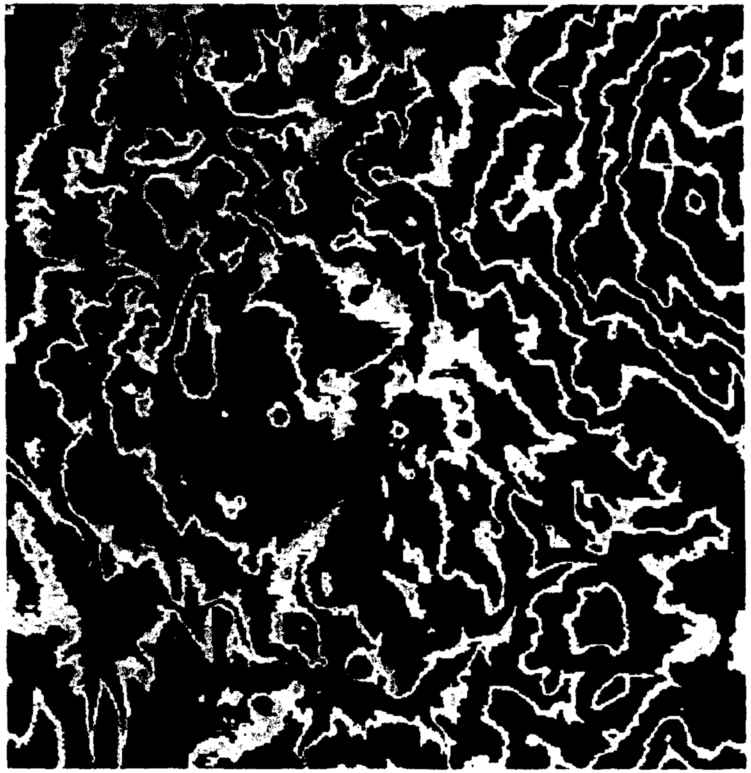
Longvalley DEM

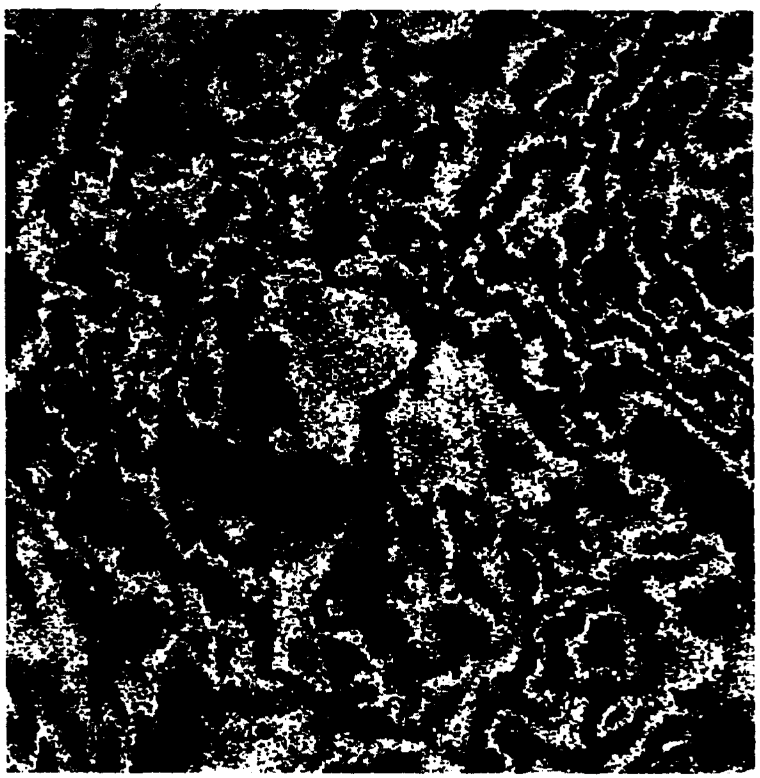
Colorwrap = 100 m



- Map is a combination of TOPSAR generated DEM of Long Valley and USGS data. Data is used to simulate interferograms that are used in height reconstruction. Simulation includes layover, shadow and masks out areas where fringe frequency is too fast for unwrapping.

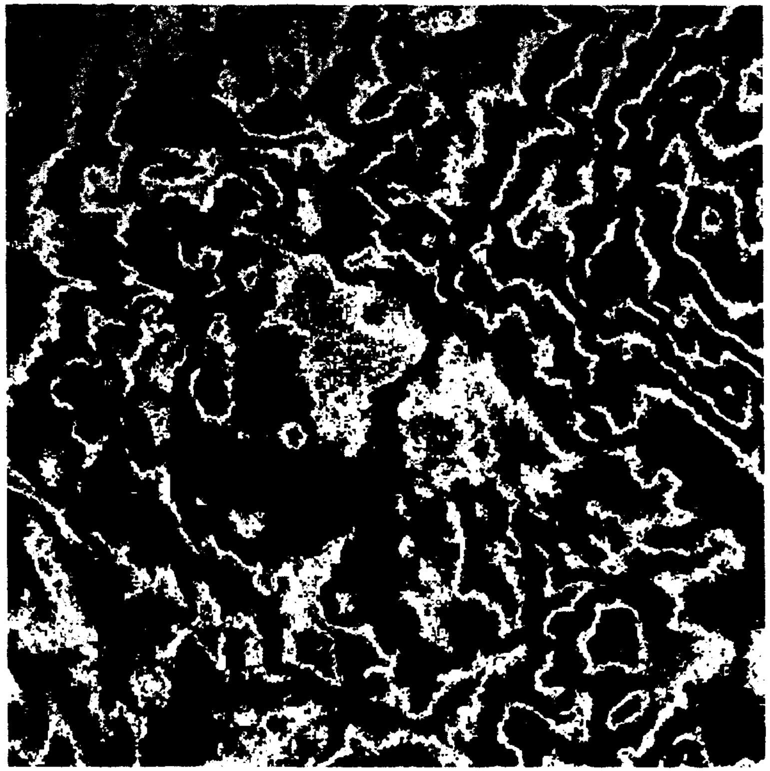
LongValley Nearest Neighbor

Noise = 10 m
Colorwrap = 100 m
r.m.s = 12.3 m
bias = -2.17 m
Coverage = 82%



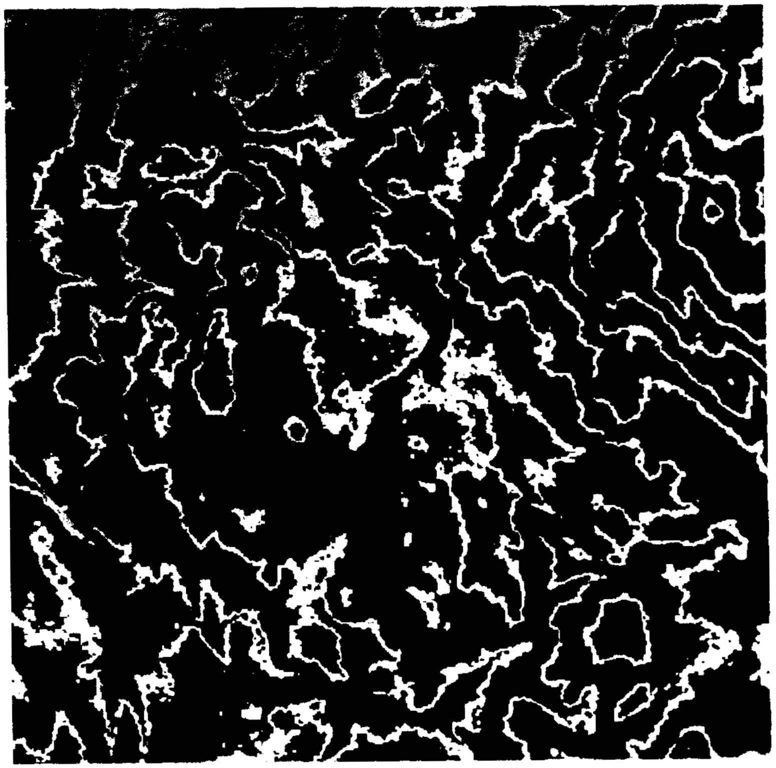
LongValley Simplical

Noise = 10 m
Colorwrap = 100 m
r.m.s = 7.87 m
bias = 2.44 m
Coverage = 82%



LongValley Convolutional

Noise = 10 m
Colorwrap = 100 m
r.m.s = 6.6 m
bias = 2.4E-2 m
Coverage = 85%



Adaptive Regridding Parameter Determination

- In the adaptive regridding process it is desired to adjust the amount of smoothing depending on the amount of topography compared to the intrinsic measurement noise.
- The amount of noise reduction and smoothing depends on the size of box used for the regrid point estimate and the amount of weighting employed.
- For computational efficiency is desired to have the weighting depend only on the measurement noise and not vary spatially with the data, however this reduces the flexibility in controlling the amount of smoothing vs noise reduction.
- The box size for fitting is determined by comparing the χ^2 residual of the surface fit to the mean of the estimated height noise as determined from the correlation in the box.
  - large residuals compared to the intrinsic noise level means that surface fit is not a good model for the local topography and therefore a smaller box size should be use.
  - each box size must be checked to insure that the points within the box the correct geometric distribution as needed by the algorithm employed.

Surface Fitting Regridding Equations

- The least squares fit to a quadratic surface (degree of surface, N =2) requires the estimation of six parameters

$$q(x,y) = a_{oo} + a_{10}x + a_{01}y + a_{11}xy + a_{20}x^2 + a_{02}y^2$$

which are obtained by solving the 6x6 linear system given below

$$\begin{bmatrix} a_{oo} \\ a_{10} \\ a_{01} \\ a_{20} \\ a_{11} \\ a_{02} \end{bmatrix} = \begin{bmatrix} \sum_i \frac{1}{\sigma_i^2} & \sum_i \frac{x_i}{\sigma_i^2} & \sum_i \frac{y_i}{\sigma_i^2} & \sum_i \frac{x_i^2}{\sigma_i^2} & \sum_i \frac{x_i y_i}{\sigma_i^2} & \sum_i \frac{y_i^2}{\sigma_i^2} \\ \sum_i \frac{x_i}{\sigma_i^2} & \sum_i \frac{x_i^2}{\sigma_i^2} & \sum_i \frac{x_i y_i}{\sigma_i^2} & \sum_i \frac{x_i^3}{\sigma_i^2} & \sum_i \frac{x_i^2 y_i}{\sigma_i^2} & \sum_i \frac{x_i y_i^2}{\sigma_i^2} \\ \sum_i \frac{y_i}{\sigma_i^2} & \sum_i \frac{x_i y_i}{\sigma_i^2} & \sum_i \frac{y_i^2}{\sigma_i^2} & \sum_i \frac{x_i^2 y_i}{\sigma_i^2} & \sum_i \frac{x_i y_i^2}{\sigma_i^2} & \sum_i \frac{y_i^3}{\sigma_i^2} \\ \sum_i \frac{x_i^2}{\sigma_i^2} & \sum_i \frac{x_i^3}{\sigma_i^2} & \sum_i \frac{x_i^2 y_i}{\sigma_i^2} & \sum_i \frac{x_i^4}{\sigma_i^2} & \sum_i \frac{x_i^3 y_i}{\sigma_i^2} & \sum_i \frac{x_i^2 y_i^2}{\sigma_i^2} \\ \sum_i \frac{x_i y_i}{\sigma_i^2} & \sum_i \frac{x_i^2 y_i}{\sigma_i^2} & \sum_i \frac{x_i y_i^2}{\sigma_i^2} & \sum_i \frac{x_i^3 y_i}{\sigma_i^2} & \sum_i \frac{x_i^2 y_i^2}{\sigma_i^2} & \sum_i \frac{x_i y_i^3}{\sigma_i^2} \\ \sum_i \frac{y_i^2}{\sigma_i^2} & \sum_i \frac{x_i y_i^2}{\sigma_i^2} & \sum_i \frac{y_i^3}{\sigma_i^2} & \sum_i \frac{x_i^2 y_i^2}{\sigma_i^2} & \sum_i \frac{x_i y_i^3}{\sigma_i^2} & \sum_i \frac{y_i^4}{\sigma_i^2} \end{bmatrix} \begin{bmatrix} \sum_i \frac{h_i}{\sigma_i^2} \\ \sum_i \frac{x_i h_i}{\sigma_i^2} \\ \sum_i \frac{y_i h_i}{\sigma_i^2} \\ \sum_i \frac{x_i^2 h_i}{\sigma_i^2} \\ \sum_i \frac{x_i y_i h_i}{\sigma_i^2} \\ \sum_i \frac{y_i^2 h_i}{\sigma_i^2} \end{bmatrix}$$

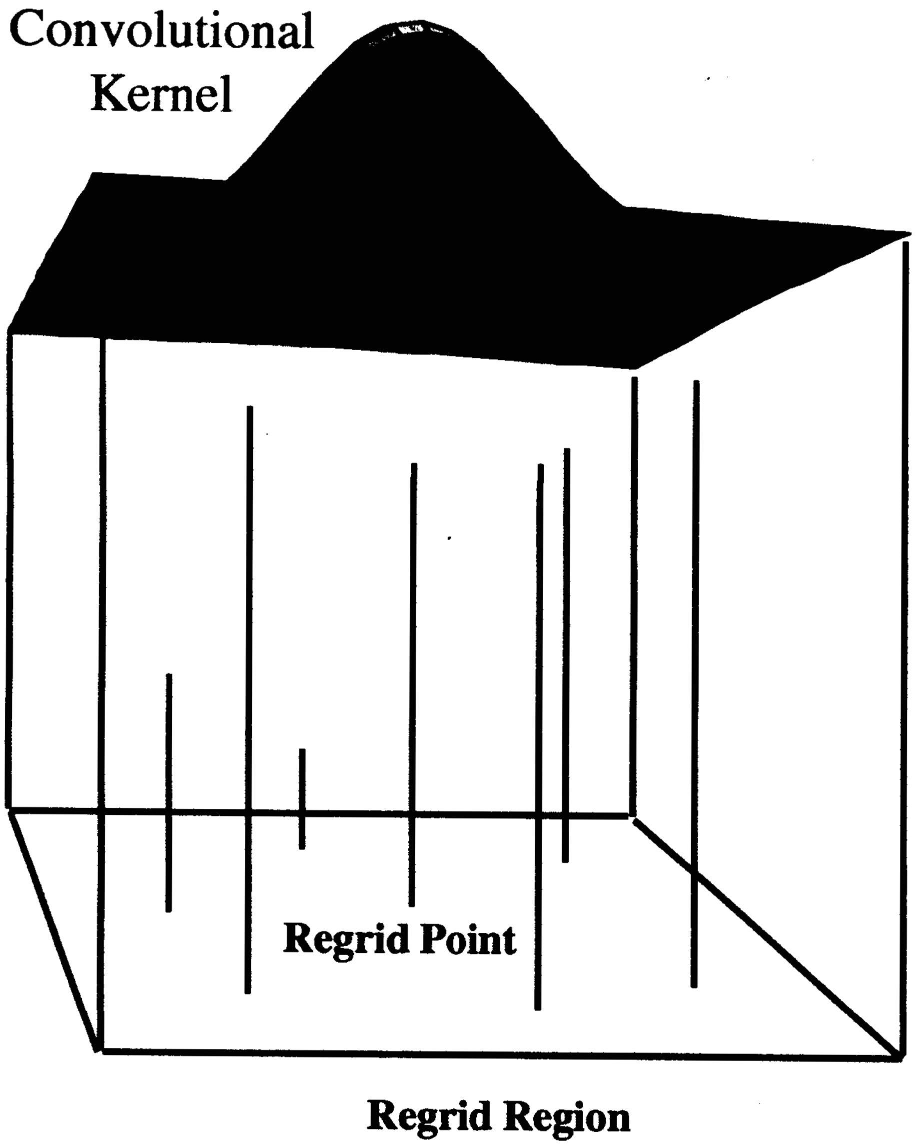
- Using Cholesky decomposition to invert the matrix and some careful bookkeeping in computing the matrix , yields the required operations per point of

$$\underbrace{\frac{1}{6}\left(\frac{(N+1)(N+2)}{2}\right)^3}_{\text{Matrix Inversion}} + \underbrace{M(N+1)(2N+1)}_{\text{Matrix Computation}}$$

M = # points in fit

Convolutional Regrid Geometry

JPL



- Box size and additional weighting adjusted depending upon the ratio of the RMS surface elevation to the mean expected height error as determined from the interferometric correlation.

- Convolutional regridding kernel is a windowed Gaussian approximating the optimal prolate spheroidal weighting function for a specified bandwidth.

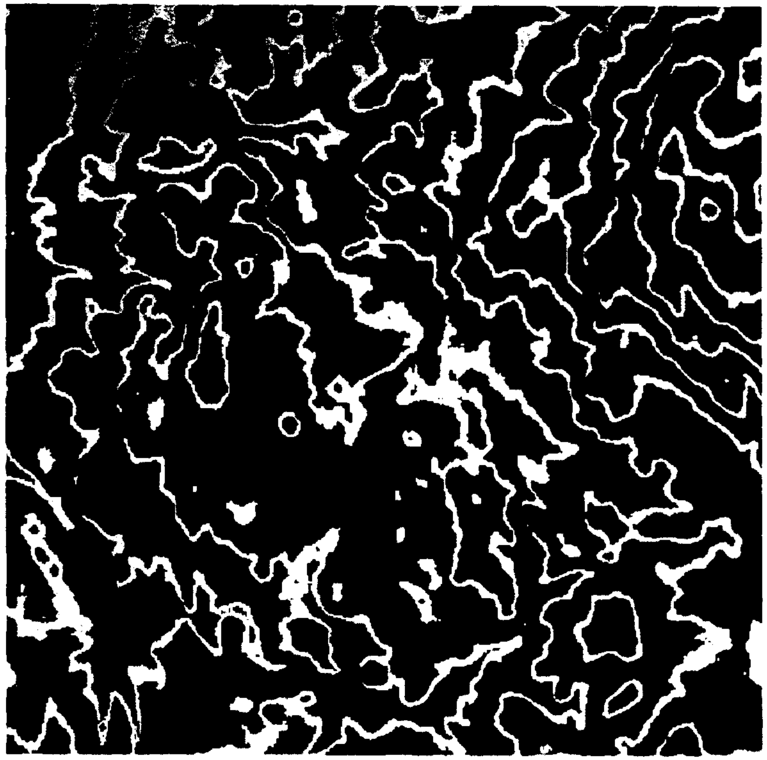
—— Measured Height

—— Regridded Height

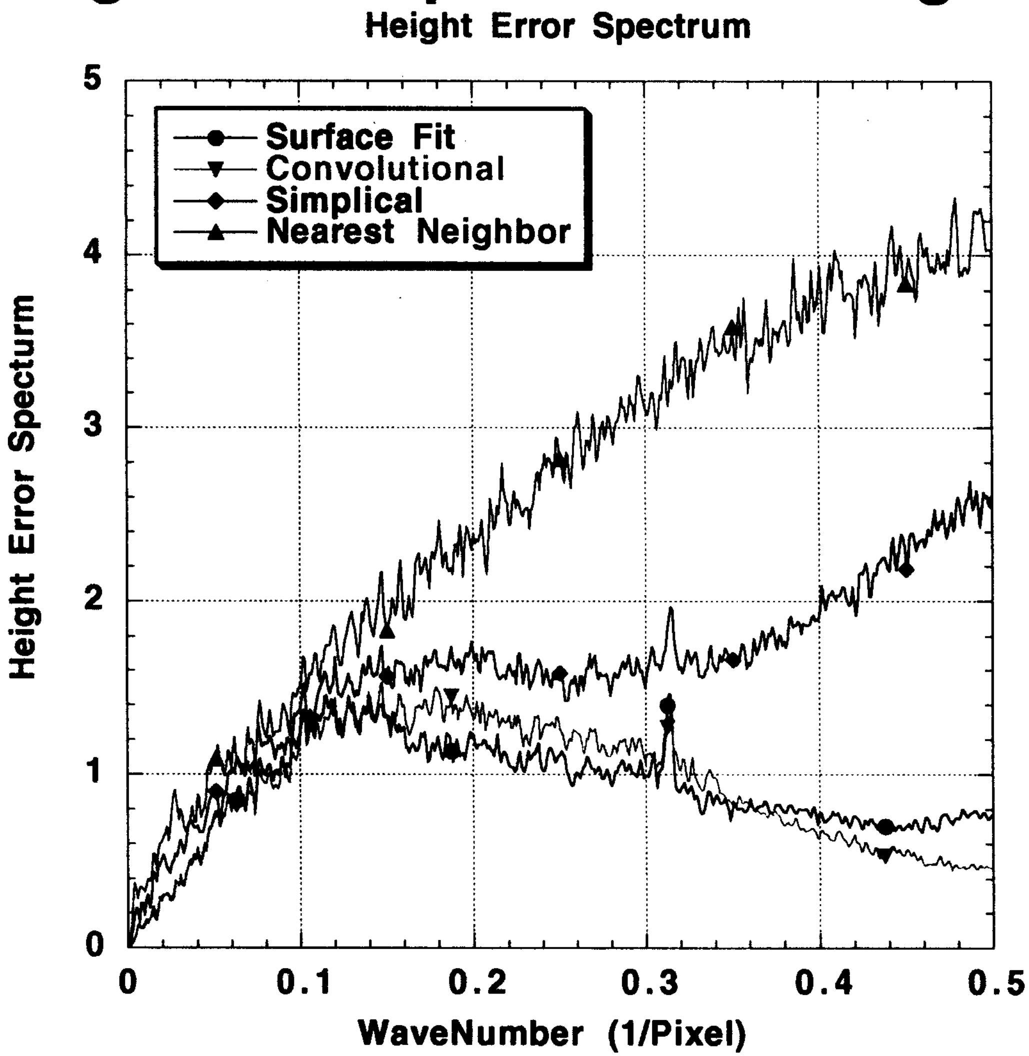
JPL

LongValley Surface Fit

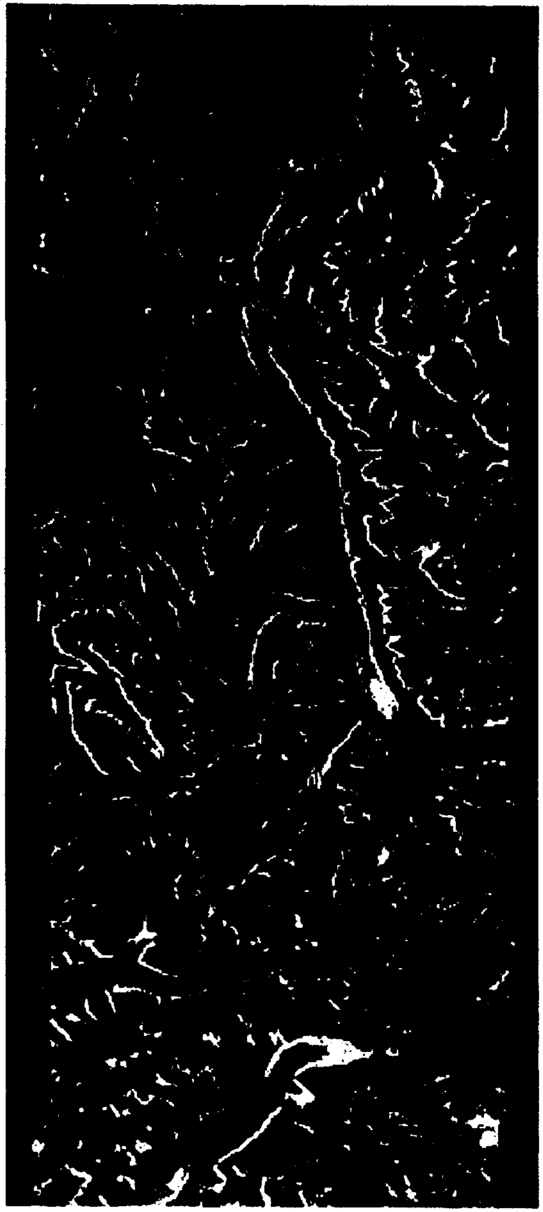
Noise = 10 m
Colorwrap = 100 m
r.m.s = 7.6 m
bias = -2.2E-3 m
Coverage = 84%



Height Error Spectrum for LongValley



Surface Fit & Convolutional Mt. Everest



Coverage: 85%-90%

Conclusions

JPL

- Four regridding algorithms for interferometric (and SAR Stereo) radar data in terms of the noise reduction capability and the amount of smoothing done to the data. Also considered in the study were adaptive algorithms where noise reduction is traded for resolution.
- Major Conclusions:
  - Nearest neighbor and Simplical algorithms can be biased if there is systematic spatially varying noise.
  - Convolutional and Surface fitting are unbiased and have the best noise reduction capability and the expense of increased computation.
  - Adaptive regridding does a good job of get the maximal noise reduction while still preserving many of the high frequency spatial features.
- Slope (and or curvature maps) can be accurately and simply computed when simplical, convolutional or surface fitting techniques are used.